An Image Processing Approach for Radioscopic Inspection of Turbine Blades

Ulf HASSLER*, Markus REHAK*
*Fraunhofer EZRT, Dr.-Mack-Str. 81, D-90762 Fuerth, Germany

Abstract. An approach for automated radioscopic inspection of turbine blades is presented. The proposed approach is based on reference-based defect recognition, together with additionally developed features in order to take into account the inspection of the cooling channels as well as the large admissible variations in wall and coating thickness of the blade. Exemplary results are presented for the available database of an image intensifier system. In that configuration, satisfying defect recognition is not possible, due to the high false alarm rate.

Author contact e-mail: ulf.hassler@iis.fraunhofer.de.

Introduction

The presented work is part of the LuFo ManuTurb project. The subproject focuses on the advancement of NDT methods for turbine blades. In particular, surface inspection by means of sheet-of-light laser scanning as well as internal defect recognition by radioscopy and CT methods are treated. Main goals are thereby the increase of the detection sensitivity as well as an advancement of the automation level by operator assistance for data interpretation. This contribution presents results of the radioscopy part.

Nickel-base alloy turbine blades are routinely inspected by radioscopy for detection of inclusions, casting flaws, voids, spillings, anomalies of cooling holes. Inspection is currently done by manual image intensifier-based radioscopic inspection of the blades in several views. Difficulties arise in interpretation of the image data due to specific conditions in imaging Ni materials at the required high resolution for detection of the specified defects. Midterm goal is here to deliver assistance to the operator personnel in case of unclear indications.

Within the present contribution, we state the current test situation with its specific challenges and possible solutions. Chapter 2 shows the solution chosen in that study. Chapter 3 shows some exemplary results. Results of that approach are presented for the available data base. As outlook, the inspection situation is customized also on a flat-panel based inspection system.

1. Current Situation

1.1 Test Situation

The operated radioscopy system is intended for visual inspection and is eqipped by an image intensifier detector. The system is typically operated at 100 kV and 3 mA, resulting in a X-ray power of approximatively 300 W. The resulting focal spot size is estimated to be 0.25 mm. Detector pixel size is also 0.25 mm. Depending on the test position, magnification factor is between 3 and 4, the average pixel size in the object plane amounts to 60 µm. The geometric unsharpness of the system lies therefore in the range of 0.5 mm to 0.75 mm. The accuracy of the handling system is specified to be 0.5 mm.

The size of the inspected blades is below 10 cm. More recent blade types possess cooling holes with a nominal diameter of approximatively 0.3 mm. The following defect types have to be detected:

- Spillings from laser drilling
- Backwall overshot
- Foreign material
- Casting defect
- Positionning and sizing of drill holes
- Voids

1.2 Identification of main challenges

A first group of difficulties concerns the Ni-alloy turbine blades and their production process. For mechanical reasons, the positioning of the casting core underlies imprecisions within the order of a drill hole diameter. The blades are coated additionally by zirconia. This layer thickness is a further source of admissible tolerances. Therefore, wall thicknesses of the blades are tolerated within a large range. Only a minimum thickness is required. Also the positioning of the laser drilling has tolerances of about one drill hole diameter.

Other difficulties are due to the nature of radioscopic imaging. The field of view per inspection position in image intensifier mode is very restricted in high resolution mode. This may lead to problems in the registration step if only unidirectional structures are present. Another effect takes place when investigating crystalline material, if the incident wavelength is of the order of the lattice spacing of the material. In that case, part of incident radiation is reflected according to Bragg condition in certain directions, where a characteristic pattern is overlaid to the absorption signal.

1.3 Possible Solution Concepts

Currently existing solutions for automatic defect recognition (ADR) in radioscopy are used in casting inspection [1-4]. Less structured objects are being inspected by referenceless methods, but more complicated geometries are preferably inspected by reference-based methods,especially if low contrasted defects have to be detected. No radioscopic ADR system applied to turbine blades is currently known. Automated operator assistance can be imagined to be realized in different ways. Integration of X-ray simulation into defect evaluation software could be used for generation of reference images or for emulation of disturbing artifacts, as for example Bragg reflexions. However, for the considered system, the following hassles were encountered:

- Simulation of image intensifier is very complex.
- Simulation of radiation reflexions is not yet available. Especially the orientation of the crystal lattice is not a priori known.
- Simulation needs CAD- or STL-description of the investigated components. Those are not available by default.

For these reasons, it was decided in that subproject to adapt an existing reference-based evaluation approach to the specific needs in turbine blade inspection. Main advantage of that approach is the implicite robustness of the method against scattered radiation by usage of reference data. However, the above mentioned different sources of admissible tolerances are problematic in case of reference based image evaluation and have to be reduced in an appropriate way.

2. Image Processing Approach

2.1 Implemented Test Strategy

A central request in inspection of modern turbine blades is the control of the cooling bore holes regarding existence, position and size. However, large admissible position tolerances of the holes may lead to high indication error rate, if standard golden image subtraction method is used. For that reason, a modified reference-based approach, using an undrilled turbine blade as reference, has been developed and implemented. A respective turbine blade of each inspected type without bore holes is necessary, as well as number, size and positions of the bores within the blade. Ideally, the bore holes can therewith be detected, counted and measured. The principle of the evaluation chain is shown in fig. 1. The grey-colored blocks show the standard procedure for reference-based evaluation. Additional steps for testing bore holes are highlighted in blue. For a reduction of influence of varying geometric properties like wall- or coating thickness, an additional stage has been integrated (yellow), which is explained in more detail in chapter 2.3. In order to take into account the high structural content of the object and the low contrast between defects and structure, the thresholding step in defect segmentation has been modified in the sense that it was made additionally dependent of the local curvature (red).

2.2 Investigation of Radiation Reflexions

An evaluation of the reflexions within the radioscopic images has been carried out, in order to estimate their possible influence. It came out, that these reflexions are looking similar for comparable inspection positions, but unfortunately no repeatable systematics has been found concerning the location within the images, even not for simple straight-forward modelling by approximation. Besides the collimated field of view, those reflexions have intensities of up to 120 grey values in the radioscopies. The implied error in material thickness is dependent on the local object thickness and varies from – 0.3 mm at 2 mm wall thickness (15 %) up to – 3.8 mm at 8 mm wall thickness (nearly 50 %).

2.3 Wall Thickness Correction

Remarkable variations in attenuation, even for identical test positions, have been identified as one of the main problems for automated evaluation of X-ray images. Fig. 2 shows an undrilled reference blade (left) and an actual test blade (left) with average grey values within the marked regions. It can be seen, that due to those large wall and coating thickness variations, which are within admissible tolerances, strong grey value differences of up to 240 grey values have been measured.

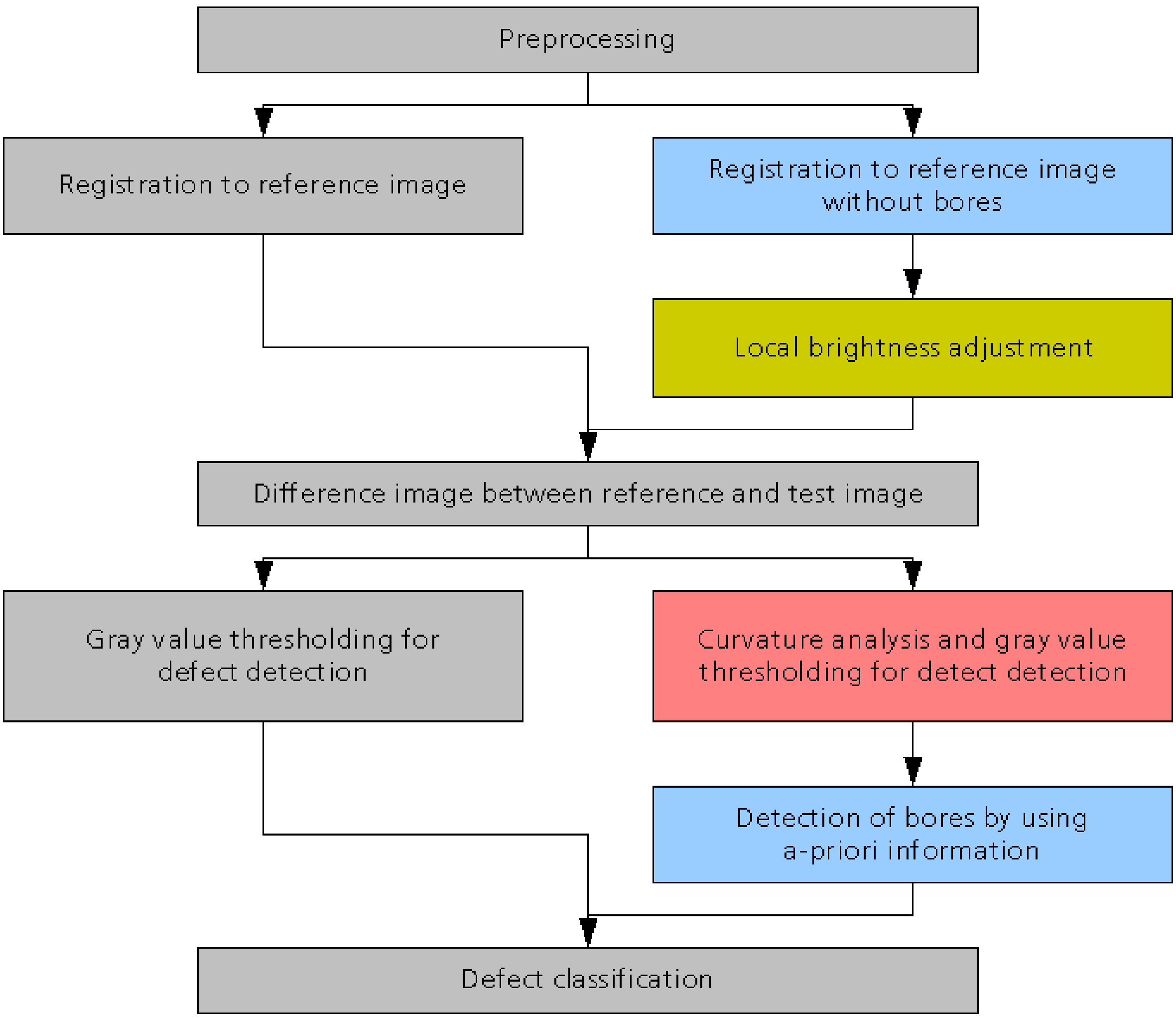

Figure 1. Schematic flow-chart of the implemented evaluation. The colored bricks were added due to the specific needs in turbine blade inspection.

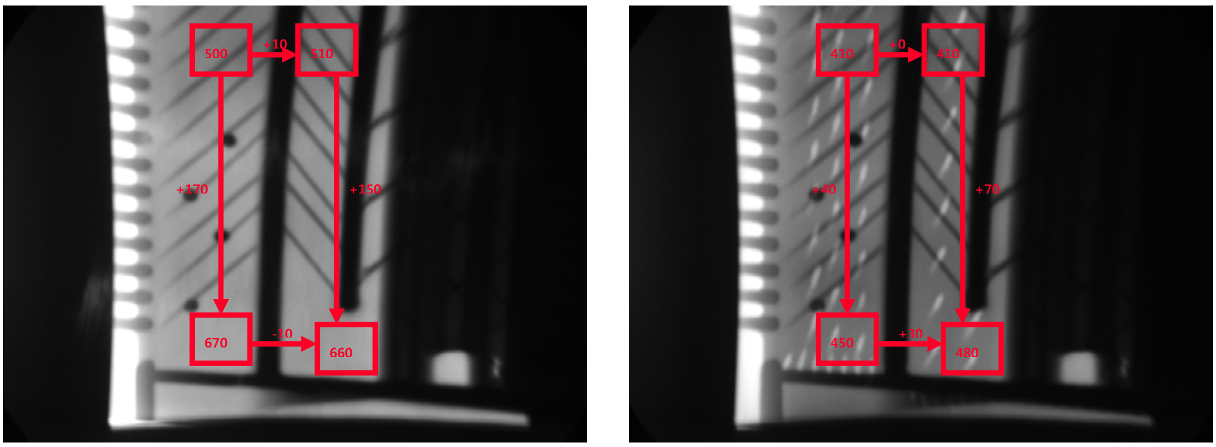

Figure 2. Comparison of intensities in test- and reference image. Different blades of same type and positions show strongly varying grey values, due to wall and coating thickness variations.

As a consequence, the detection of defective structures within difference images will be hindered or impossible, because those grey value differences are much more important than local contrast of the defects. A constant adaptation of average image intensity did not compensate enough for that purpose, and a large number of undetected defects and false positive detections occurred.

Goal of the implemented correction approach is a reduction of that important intensity differences. Basic assumption is, that wall thicknesses of front- and backside of the blade do not vary abruptly within a small neighborhood. Total wall thickness of the blade is modeled individually for test- and reference blade. For that, all regions and structures not belonging to front- or back side of the blade, are removed from the projection image. The remaining areas are approximated by a two dimensional polynomial function. Fig. 3 shows an exemplary result of that approach. The left image shows the difference image without correction, the right one with wall thickness correction. Especially in the upper image area, a considerable reduction of the intensity differences can be stated. An overshot defect becomes visible, which is not detectable without correction. However, horizontal bright and dark stripes are still visible in the lower image region, which are possibly due to Bragg reflexions. This artifact could not be reduced by the polynomial model of second degree. Those effects may therefore still be a source for misdetection of small defects.

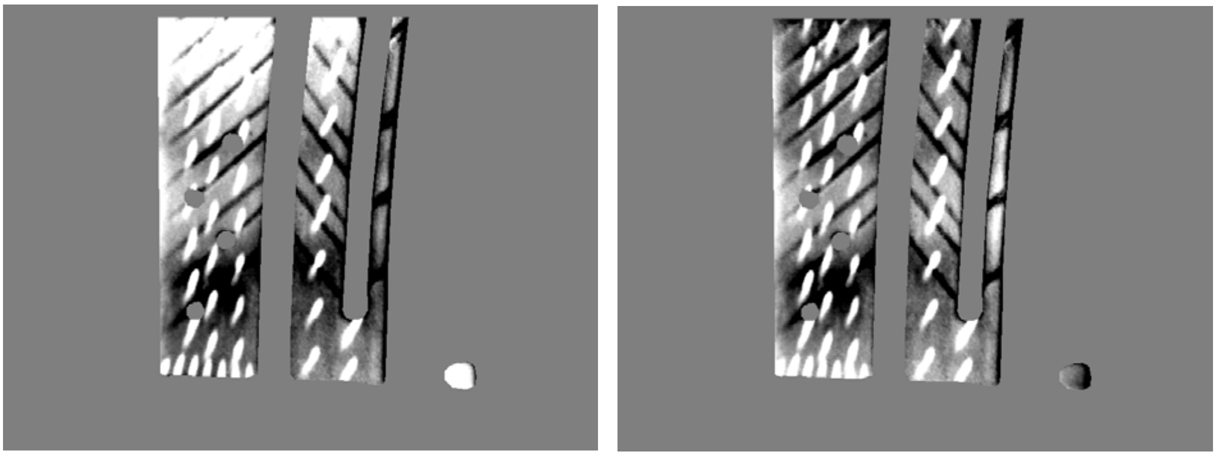

Figure 3. Comparison of difference image without (left) and with application of the wall thickness correction. Especially in the upper image area, an improvement can be stated, where small defects become visible.

3. Results

3.1 Data

For the reported work, three different turbine blade types were available:

- Type 1: Blade with 13 test positions. 27 data sets (10 IO, 16 NIO, 1 undrilled)
- Type 2: Older blade type without cooling holes. 3 data sets (3 NIO)
- Type 3: Blade with 9 test positions. 10 data sets (7 IO, 2 NIO, 1 undrilled)

The supply of undrilled blades is cumbersome, because it has to be gated out of the production process for X-ray inspection. For those data sets, wall thickness characteristics as well as test and quality parameters were set up.

3.2 Examples

3.2.1 Undrilled Blade

That blade type has no cooling holes. Therefore, the simple subtraction approach can be applied, an undrilled reference blade is not necessary. The difficulty on that blade type is the absence of any horizontal structure, so that registration of the test position is not always possible. Fig. 4 shows the detection of an indentation, after a good registration. The evaluation was effected without wall thickness correction. Fig. 5 shows a blade with washout defect and bad registration. In that case, the defective areas are correctly detected, but a lot of false positives are also detected.

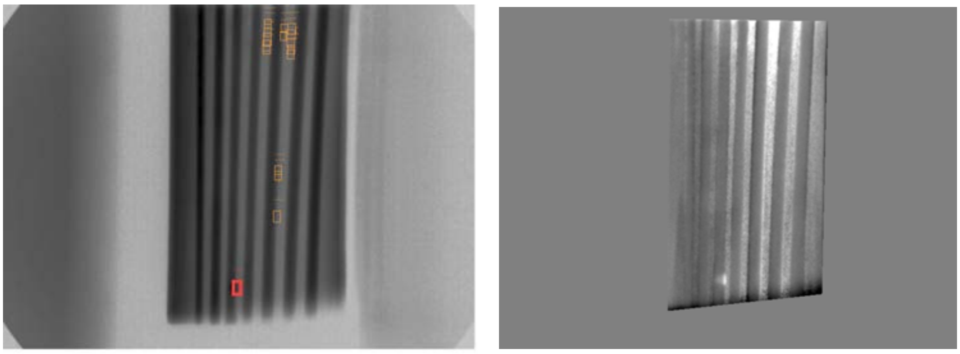

Figure 4. Automated detection of an indentation. Only uncritical false positives are detected (left). Difference image is shown on the right side.

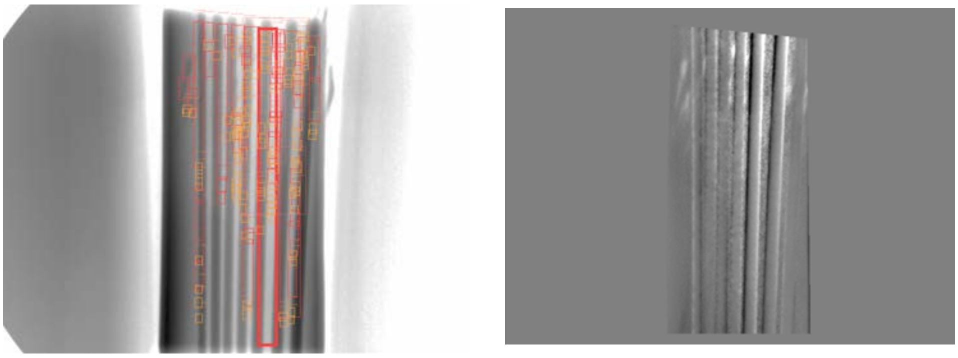

Figure 5. Automated detection of a washout defect. A large number of false positives are detected, due to incorrect registration step.

3.2.2 Drilled Blade

An example of a drilled blade with an overshot defect is shown in fig. 6. It can be seen, that the defect can be segmented correctly, even against the neighboring bore hole. Bore hole identification works well, no bore hole has been detected as defect. However, a large number of false positives is detected, although oftentimes with small extent. They appear frequently at the border of struttings or other blade structures. A particular concentration can be observed in a region which appears dark in the difference image and which is due to deficient compensation of the wall thickness correction or remaining reflexions. A large part of the false positives can certainly be rejected by a final classification stage.

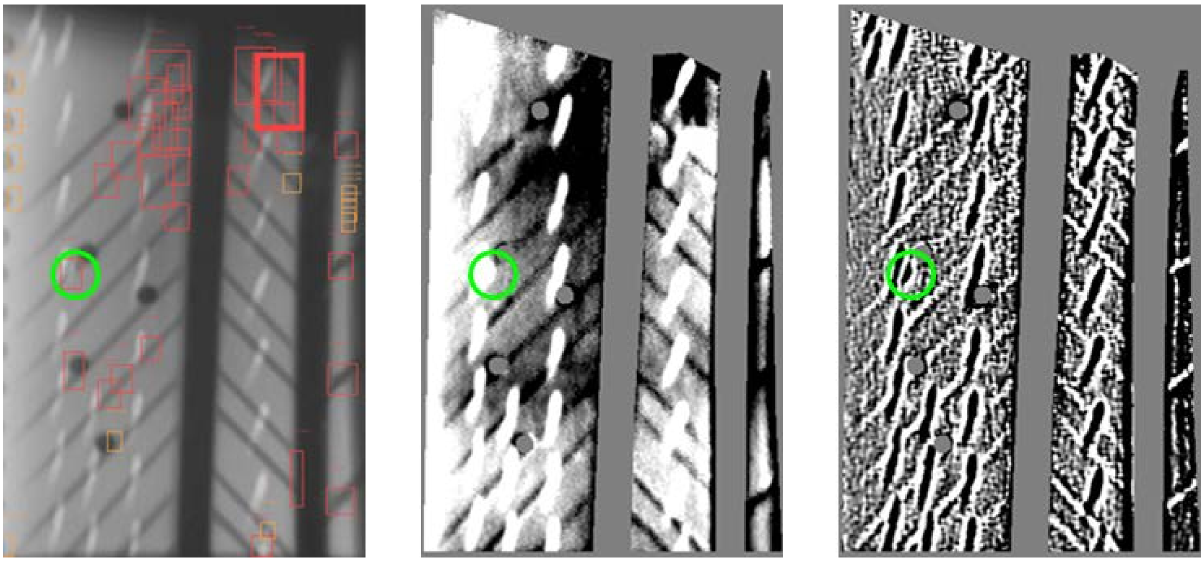

Figure 6. Automated detection of an overshot defect. Left: Original image with segmented defects, Middle: Difference image, Right: Curvature image. The defect was correctly segmented and differentiated from the bore hole. False positives appear at strutting structures and increased in a region which appears dark in the difference image.

3.2.3 Discussion

The evaluation of the test data base showed that most of the present defects can be detected, but at the cost of a number of false positives, which is not acceptable for industrial application. The following list gives an overview of items complicating automated evaluation:

- Different X-ray parameters in all test positions
- High geometric unsharpness
- Predominant vertical blade structures
- Insufficient reduction of radiation reflexions

3.3 Comparison to Flat Panel Imaging

Due to the poor results on image intensifier data, three blades of type 1 were investigated on an X-ray system equipped with a flat panel detector. Such type of inspection system has the following advantages:

- Imaging of the whole blade in one test position with the same object resolution. Therefore, number of test positions can be reduced from 13 to 7.
- Due to the larger inspection area, respective the whole blade, the registration step can be performed much more stable.
- Higher dynamic range of the flat panel results in higher image contrast, therefore smaller differences in material thickness and with that smaller defects can be detected.

A disadvantage is certainly that a live-observation of the blade in movement may not be possible. Figure 7 shows an example of blade type 1. There was no undrilled reference blade available. Compared to image intensifier data, much less false positive detections are observable. In addition, two small defects can be seen respectively detected, which were not by the image intensifier configuration.

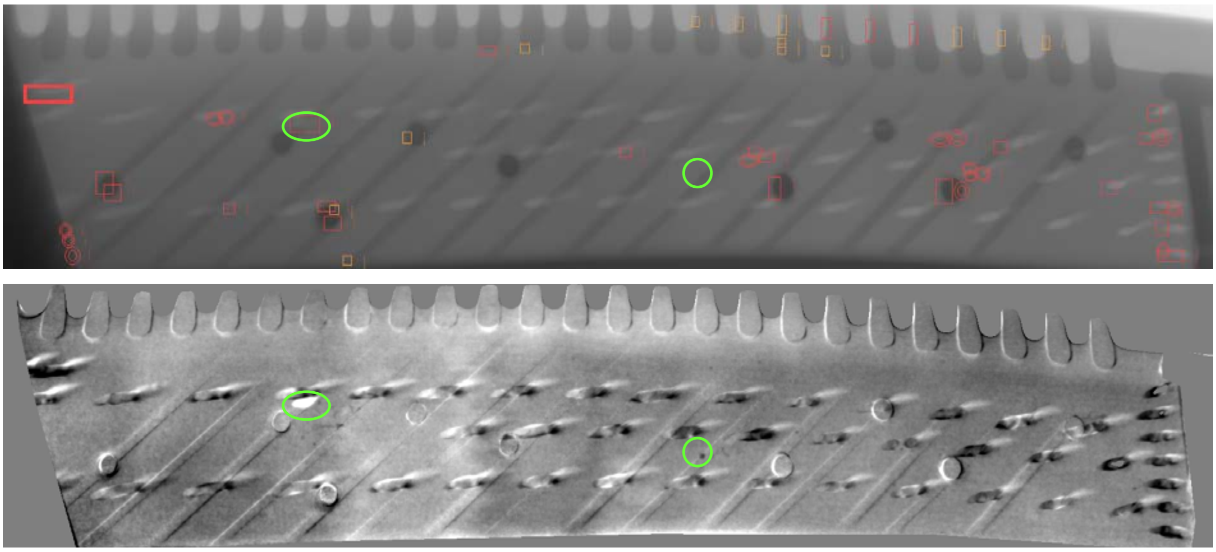

Figure 7. Automated evaluation of a flat panel data set of blade type 1. Original image with detected defects (top), and difference image (bottom). The left green defect has not been visualized and detected within the image intensifier data.

4. Conclusion

Within the presented ManuTurb subproject, a study was performed, in order to evaluate the potential of automated radioscopic turbine blade inspection for operator assistance. An existing reference-based evaluation approach has been adapted to the specific demands of blade inspection, in particular drill hole inspection and a compensation for wall and coating thickness variations. The original goal to obtain a nearly ready-for-use system, could not be fulfilled. Most of the defects within the available data base could be detected, but at costs of a very high false positives rate, which is not acceptable in routine inspection. Main reasons for that is the used image intensifier system and the remaining strong influence of radiation reflexions. Further investigations should be performed on a much larger data base acquired on a flat panel system, in order to get realistic estimations of reachable detection performance and false positive rates. Additionally, measures should be taken into account for reduction of Bragg reflexions, for example the use of anti-scatter grids.

Acknowledgement

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